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ESTIMATING THE KINETIC LUMINOSITY FUNCTION OF JETS FROM GALACTIC X-RAY BINARIES

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ABSTRACT

By combining the recently derived X-ray luminosity function for Galactic X-ray binaries (XRBs) by Grimm et al. (2002) and the radio–X-ray–mass relation of accreting black holes found by Merloni et al. (2003), we derive predictions for the radio luminosity function and radio flux distribution (logN/logS) for XRBs. Based on the interpretation that the radio–X-ray–mass relation is an expression of an underlying relation between jet power and nuclear radio luminosity, we derive the kinetic luminosity function for Galactic black hole jets, up to a normalization constant in jet power. We present estimates for this constant on the basis of known ratios of jet power to core flux for AGN jets and available limits for individual XRBs. We find that, if XRB jets do indeed fall on the same radio flux–kinetic power relation as AGN jets, the estimated mean kinetic luminosity of typical low/hard state jets is of the order of $\langle W_{\rm XRB}\rangle \sim 2\times 10^{37}\,{\rm ergs\,s^{-1}}$, with a total integrated power output of $W_{\rm XRB} \sim 5.5\times 10^{38}\,{\rm ergs\,s^{-1}}$. We find that the power carried in transient jets should be of comparable magnitude to that carried in low/hard state jets. Including neutron star systems increases this estimate to $W_{\rm XRB,tot} \sim 9\times 10^{38}\,{\rm ergs\,s^{-1}}$. We estimate the total kinetic energy output from low/hard state jets over the history of the Galaxy to be $E_{\rm XRB} \sim 7\times 10^{56}\,{\rm ergs}$.

Subject headings:

1. INTRODUCTION

X-ray binaries (XRBs) have long been thought of as classic examples of accretion flows with little or no complicated outflow physics in the way of understanding the dynamics of these systems. It was not until recently that jets and outflows were realized as important ingredients in the process of accretion even in XRBs. The reason for this late appreciation is the fact that black hole XRBs are less radio loud than AGNs by about 4 orders of magnitude (Heinz & Sunyaev 2003).

Accreting neutron star binaries, which are now also known to regularly produce radio emitting jets (Fender 2005), are yet another factor of 30 more radio quiet than black hole XRBs (Fender & Kuulkers 2001; Migliari et al. 2003). This further reduction in radio flux has made quantitative analysis of neutron star jets difficult to the point that rather little is known about them at present. Therefore, we will henceforth focus on the properties of jets from black hole XRBs throughout most of this paper and will present an extension of our work in §3.5 to neutron star XRBs.

In consequence, while XRBs are among the brightest X-ray sources in the sky, their radio output is rather weak. This, and the fact that the number of Galactic XRBs is much smaller than the number of AGNs, are to blame for the fact that very little information about the radio power from XRB jets exists and that the physical properties of these jets are even less well known that those of AGN jets (which by themselves still pose many questions as to their exact makeup and dynamics).

Two types of radio loud jet-like outflows have been observed in black hole XRBs. Following transitions in the X-ray spectral state, one can often observe bright radio flares, which are optically thin and show a powerlaw temporal decay on day timescales. The radio emission can be resolved on sub-arcsecond scales and shows proper motion (Mirabel & Rodríguez 1994; Hjellming & Rupen 1995; Fender et al. 1999). These ejections can carry a large amount of power, but are relatively rare. The second kind of jet-like outflow is associated with the so-called low/hard state in black hole XRBs (see McClintock & Remillard 2003, for a thorough review on X-ray states in XRBs). These outflows show a flat, optically thick radio spectrum and typically do not show a temporal decay. Only two of these sources have been resolved, showing a collimated jet on milli-arcsecond scales (Stirling et al. 2001; Dhawan et al. 2000; Fuchs et al. 2003). Consequently, these types of flows are referred to as "steady/compact" jets, and for the remainder of this paper, we will be mostly concerned with these types of jets.

Steady, compact, flat spectrum jets are observed in virtually every Galactic black hole XRBs in the low/hard state that is accessible to radio instruments. Significant progress in our understanding of XRB jets has recently been made when a relation between the radio luminosity from these steady, compact jets and the hard X-ray luminosity was discovered in low/hard state source (Corbel et al. 2002; Gallo et al. 2003) . This relation has since been found to extend from stellar mass black holes all the way up the black hole mass scale to AGN jets (Merloni et al. 2003; Falcke et al. 2004). In the remainder of this paper we will refer to this relation as the "fundamental plane of black hole activity" (FP hereafter).

The FP relation expresses both the fact that the radio luminosity from compact jets is non-linearly correlated with the X-ray flux, as had already been discovered in the case of XRBs, as well as the non-linear dependence of radio flux on black hole mass. The latter is responsible for the fact that AGN are so much more radio loud than XRBs. These relations can be understood naturally if the physics underlying jet formation (ultimately, strong gravity and MHD in the inner accretion flow) are invariant under changes in black hole mass (Heinz & Sunyaev 2003).

This scale invariance implies that a relation between the radio luminosity $L_{\rm r}$ emitted by the jet and the kinetic jet power

$W_{\rm kin}$ is underlying the radio-X-ray-mass relation. For reasonable parameters[1], this relation takes on the form $L_{\rm rad} \propto W_{\rm kin}^{1.42-\alpha_{\rm r}/3}$, where $\alpha_{\rm r} \approx 0$ is the radio spectral index. Together with the recent discovery of the FP, this relation can provide a powerful diagnostic for studying the properties of jets.

A second recent insight that has spurred heightened interest in the statistical study of XRBs is the firm determination of the Milky Way XRB X-ray luminosity function (Grimm et al. 2002). In this paper, we will couple the information contained in the XRB luminosity function with the predictive power of the FP relation to derive some of the missing statistical properties of the XRB jet population needed in planning observation campaigns for XRBs and in modeling the jets of XRBs and their impact on the interstellar medium.

In §2 we will derive the kinetic luminosity function for Milky Way low/hard state XRB jets, parameterized by the unknown normalization of the kinetic power – radio power relation underlying the fundamental plane relation. In §3, we will present an estimate of that normalization derived from AGN jets and the available limits for individual XRBs, and apply it to the XRB jet population to derive the absolute kinetic luminosity function. In §4 we derive, as corollaries to the kinetic luminosity function, the predicted radio luminosity function of XRB jets and the predicted Galactic radio logN/logS distribution. Section 5 summarizes our results.

2. DERIVING THE KINETIC LUMINOSITY FUNCTION OF BLACK HOLE XRBS IN THE LOW/HARD STATE

The discovery of the FP relation has enabled a number of diagnostic tools to be developed for accreting black holes (Merloni 2004; Maccarone 2004; Heinz 2004; Heinz & Merloni 2004; Markoff 2005). Since the current theoretical understanding of the FP relation is based on a relation between kinetic jet power and radio luminosity, it is now possible to convert a radio luminosity function into a kinetic luminosity function (Heinz et al. 2005). This is a powerful and useful technique for AGN jets, where we can measure the radio luminosity function and have good estimates of the kinetic power in a number of sources. In XRBs we have neither, due to the characteristically lower radio fluxes of XRB jets (which has delayed their mass discovery by 30 years relative to the large known sample of AGN jets) and the lack of good estimators of kinetic power in these sources.

However, the small dispersion in black hole mass in black hole XRBs and the recently published X-ray luminosity function for XRBs (Grimm et al. 2002) allow us to use the FP relation to construct both a predicted radio luminosity function and a kinetic luminosity function. These estimates are necessarily subject to considerable uncertainty from a number of unknowns: (a) The conversion of the total XRB luminosity function to a black hole luminosity function (essentially, the black hole fraction of XRBs), (b) the normalization of the kinetic jet power for a given radio power (this holds for AGNs as well), and (c) the mass distribution of stellar mass black holes. We will parameterize our results in terms of the fiducial values we assume for these unknowns to allow for easy adjustment with future improvements in the knowledge of these parameters.

[1] For an electron spectrum with powerlaw index $p = 2$ and proportionality between kinetic jet power and magnetic energy density, $W_{\rm kin} \propto B^2$, i.e., for magnetically driven jets

2.1. *The XRB luminosity function*

The FP relation implies that below a certain critical accretion rate $\dot{m}_{\rm crit} \equiv \dot{M}_{\rm crit}/\dot{M}_{\rm Edd} \sim 0.01$, there exists a correlation between the mass of a black hole M, its radio luminosity $L_{\rm r}$, and its X-ray luminosity $L_{\rm x}$ of the form

$$L_{\rm r} = L_0\, l_{\rm x}^{0.6} M^{0.78} \tag{1}$$

$$L_0 \equiv 1.6 \times 10^{30}\,{\rm ergs\,s^{-1}} \tag{2}$$

where, for convenience, we expressed the X-ray luminosity in terms of the Eddington luminosity $L_{\rm Edd} = 1.3 \times 10^{38}\,{\rm ergs\,s^{-1}}$ of a one solar mass object: $l_{\rm X} \equiv L_{\rm X}/L_{\rm Edd}$. Following the interpretation of Merloni et al. (2003); Fender et al. (2004b), we will assume in the following that the transition at $\dot{m}_{\rm crit}$ is due to a state change as observed in XRBs, where low luminosity sources switch into the low/hard state. In XRBs, which we are concerned with here, steady, flat spectrum jets are closely associated with the low/hard state. The details of this transition are irrelevant, we will simply use the associated X-ray luminosity as an upper bound on the luminosity function. For a fixed black hole mass $M = 10\,M_{\odot}\,M_{10}$, this transition corresponds to a critical X-ray luminosity $l_{\rm X,crit} = 10\,M_{10}\,\dot{m}_{\rm crit}$. Miyamoto et al. (1995); Maccarone (2003) showed that the transition from high/soft to low/hard state actually occurs over a range of values for $\dot{m}_{\rm crit}$, and that a hysteresis exists with sources on the descending luminosity branch staying in the high/soft state longer (to lower luminosities) than ascending sources, which make the state transition from hard to soft at higher luminosities. Fender et al. (2004b) show how the properties of XRB jets correlate with the position of a source on this hysteresis track. We will comment on the impact the uncertainty of $\dot{m}_{\rm crit}$ has on our results in §3.3.

Following Heinz & Sunyaev (2003), the radio luminosity $L_{\rm r}$ of the flat spectrum core of the jet is related to the jet power $W_{\rm jet}$ by

$$W_{\rm jet} = W_0 \left(\frac{L_{\rm r}}{L_0}\right)^{\frac{1}{1.42-\alpha_{\rm r}/3}} \tag{3}$$

where $\alpha_{\rm r} \equiv -\partial(\ln L_{\nu})/\partial(\ln \nu) \sim 0$ is the radio spectral index an close to zero for the flat spectrum sources under consideration. Henceforth we will use $\alpha_{\rm r} = 0$ unless noted otherwise. W_0 is currently not well known: it is the normalization of the kinetic jet power in relation to its radio luminosity[2]. It is not well known because jet power is still a very difficult quantity to measure, even after four decades of research on jets. We will attempt to estimate it below and will carry it through the algebra as a parameter until then. Combining eqs. (1) and (3), we can now write

$$l_{\rm x} = \left(\frac{W_{\rm jet}}{W_0}\right)^{\frac{1.42-\alpha_{\rm r}/3}{0.6}} M^{-\frac{0.78}{0.6}} \tag{4}$$

We will use the X-ray luminosity function for the Milky Way XRBs provided by Grimm et al. (2002) (see Fig. 12 in their original paper). Where appropriate, we provide estimates based both on the actual data they derived (numerically

[2] Naively, W_0 can be taken as a radiative efficiency, though it should be kept in mind that most of the radiation is emitted at high frequencies, thus the radiative efficiency is often times not well defined, as the high energy cutoff of individual sources is hard to measure and it is not clear which parts of the spectrum actually arise in the jet and which arise in the accretion flow.

integrated) and parameterized using the powerlaw approximation $dN/dl = N_0 l^{-\beta}$, fitted by Grimm et al. (2002) to give:

$$\frac{dN_{\rm HMXB}}{dl_{\rm x}} = 0.7 l_{\rm x}^{-1.6} \tag{5}$$

$$\frac{dN_{\rm LMXB}}{dl_{\rm x}} = 5 l_{\rm x}^{-1.4} \tag{6}$$

for $l_{\rm x} < 1$ as well as the actual data. The X-ray luminosity function does not show a low luminosity cutoff. But at low luminosities the observed number of sources is very small due to the sensitivity limits of the ASM on RXTE. However, a comparison with higher sensitivity (but smaller sky coverage) ASCA data of the Galactic Ridge Survey (Sugizaki et al. 2001) show that the XRLF does not require a cutoff down to $\sim$few 10^{33} ergs s^{-1} (Grimm et al. 2002).

The radio-X-ray correlation in XRBs has been observed down to X-ray luminosities of about $l_{\rm x} \gtrsim 10{-}4$ in the case of GX 339-4. While there is reason to believe that the radio-X-ray relation might break down at very low luminosities (the synchrotron X-ray component from the jet scales more slowly with $\dot{m}$, $F_{\rm x,synch} \propto \dot{m}^{1-1.8}$ than the X-rays from the accretion flow, $F_{\rm x,acc} \propto \dot{m}^{2-2.3}$ Merloni et al. 2003; Heinz 2004; Yuan & Cui 2005), we will take $l_{\rm x,min} = 10^{-4}$ as a secure upper limit on the low luminosity cutoff of the radio-X-ray relation.

The relative fraction of black holes as a function of $l_{\rm x}$ in both the LMXB and HMXB luminosity functions is unknown. Thus, for lack of better knowledge, we will use the ratio of observed black hole to neutron star XRBs, which is about 10%. We parameterize this unknown fraction as $\zeta = [dN_{\rm BH}/dl_{\rm x}]/[dN_{\rm NS}/dl_{\rm x}] = 0.1\zeta_{0.1}$ and assume that the fraction of black holes is constant as a function of $l_{\rm x}$. Given the uncertainty in these estimates and the lack of knowledge of the black hole mass function, we will henceforth assume that the mean black hole mass is $10\,M_{\odot} M_{10}$ and evaluate all quantities for this black hole mass.

The instantaneous kinetic luminosity function for jets from Galactic black holes is then

$$\frac{dN}{dW_{\rm jet}} = \frac{1.42 - \alpha_{\rm r}/3}{0.6 W_0} M^{-\frac{0.78}{0.6}} \left(\frac{W_{\rm jet}}{W_0}\right)^{\frac{0.82-\alpha_{\rm r}/3}{0.6}} \frac{dN}{dl_{\rm x}} \tag{7}$$

for $l_{\rm min}^{0.42} W_0 M^{0.55} < W_{\rm jet} < \dot{m}_{\rm crit}^{0.42} W_0 M^{0.55}$. For the powerlaw parameterizations, we have

$$\frac{dN_{\rm HMXB}}{dW_{\rm jet}} \approx \left(\frac{W_{\rm jet}}{W_0}\right)^{\alpha_{\rm r}/3-2.42} \frac{M_{10}^{0.78}}{W_0}\zeta_{0.1} \tag{8}$$

$$\frac{dN_{\rm LMXB}}{dW_{\rm jet}} \approx 4\left(\frac{W_{\rm jet}}{W_0}\right)^{\alpha_{\rm r}/3-1.95} \frac{M_{10}^{0.52}}{W_0}\zeta_{0.1} \tag{9}$$

in the same bounds. All that is left to do is the determination of W_0 — clearly the most difficult and uncertain part of this exercise.

3. ESTIMATING THE ABSOLUTE KINETIC LUMINOSITY FUNCTION

3.1. *Estimating W_0*

3.1.1. *Estimates of the kinetic power in AGN jets*

Information on the kinetic power from XRB jets is just starting to become available. We will discuss the available estimates and how they can be used to constrain W_0 in §3.1.2. First, however, we will consider the case of AGN jets, for which information about the kinetic power is readily available and undisputed in a number of important cases. There are three AGN jet sources in the sample used to derive the FP relation by Merloni et al. (2003) which have reliable estimates of the jet power: M87, Cygnus A, and Perseus A. These estimates are derived from average powers on very large spatial scales in the cases of Cygnus A and Perseus A, while for M87 power estimates exist both for large spatial scales from X-ray cavities, and for jet scales (Bicknell & Begelman 1996).

We can use these sources to estimate W_0 (Heinz et al. 2005). We should keep in mind, though, that the sources each have some offset from the fundamental plane relation due to the intrinsic scatter around the plane. Furthermore, the *large scale* power estimates are time averaged (over times much longer than the dynamical time of the central jet that is currently producing the radio emission) and might not be representative of the current jet power. However, the fact that the estimate we get from M87 alone (where the large scale power estimate agrees with the smaller scale estimate) is consistent with the ones obtained from the other two sources indicates that we are probably not too far off. It should also be noted that all of these sources show compact, flat spectrum jets, which is critical if we want to use them as templates for low/hard state jets from Galactic XRBs.

The rough power estimates for the three sources are: $W_{\rm jet} \approx 10^{45.7}\,{\rm ergs\,s^{-1}}$, $10^{44}\,{\rm ergs\,s^{-1}}$, and $10^{44.5}\,{\rm ergs\,s^{-1}}$ for Cygnus A, M87, and Per A respectively (Carilli & Barthel 1996; Bicknell & Begelman 1996; Forman et al. 2005; Fabian et al. 2002), while their core radio luminosities are $10^{41.4}$, $10^{39.8}$, and $10^{41.7}\,{\rm ergs\,s^{-1}}$, respectively. Thus, the normalization constants we derive for the sources are $W_{0,\rm CygA} \sim 6.3\times10^{37}\,{\rm ergs\,s^{-1}}$, $W_{0,\rm M87} \sim 2\times10^{37}\,{\rm ergs\,s^{-1}}$, and $W_{0,\rm PerA} \sim 2.6\times10^{36}\,{\rm ergs\,s^{-1}}$, each carrying *considerable* uncertainty from the estimate of the kinetic power and from the fact that the sources scatter around the fundamental plane.

We can also calculate what the radio power should be if there were no scatter around the relation, by estimating the unbeamed radio flux from the X-ray luminosity and the mass of the objects, using the FP relation. In this case, the normalization constants are $W_{0,\rm CygA} \sim 10^{38}\,{\rm ergs\,s^{-1}}$, $W_{0,\rm M87} \sim 6.3\times10^{37}\,{\rm ergs\,s^{-1}}$, and $W_{0,\rm PerA} \sim 3.7\times10^{37}\,{\rm ergs\,s^{-1}}$, which is significantly more homogeneous.

This expression is more appropriate to use in an average sense when considering a large sample of sources, since the radio emission probably carries the biggest fraction of the scatter in the fundamental plane relation due to variations in relativistic beaming, black hole spin, and spectral index. In this particular case it is also more appropriate because we are using the X-ray luminosity of XRBs and the fundamental plane to convert X-ray fluxes into radio fluxes. Thus, using X-ray fluxes to calibrate this method seems to us to be the most consistent approach. We will therefore use this "corrected" estimate of the efficiency, which averages to

$$W_0 \approx 6.2\times10^{37}\,{\rm ergs\,s^{-1}}\mathcal{W}_{37.8} \tag{10}$$

with about an order of magnitude uncertainty. We will carry $\mathcal{W}_{37.8}$ through the rest of the paper to allow the reader to adjust for future improvements and different personal preferences in this value.

3.1.2. *Limits from power estimates of XRB jets*

There is relatively little information about the kinetic power output of individual Galactic XRBs that we could use to cal-

ibrate W_0. The best information available to date is on the jet in Cygnus X-1. The compact jet is resolved on scales of 15 mas, and using a simple Blandford–Koenigl model (Blandford & Koenigl 1979) to describe the radio emission, one can put a lower limit of $W_{\rm jet} > 3 \times 10^{33}\,{\rm ergs\,s^{-1}}$, which is very likely much lower than the true kinetic power. For the radio flux of 12 mJy, this translates to a lower limit of $W_0 > 10^{34}\,{\rm ergs\,s^{-1}}$ (Stirling et al. 2001).

Based on the IR observations of compact jet in GRS 1915+105, Fender & Hendry (2000) argue that the normalization for the kinetic power must be larger than $W_0 > 2 \times 10^{35}\,{\rm ergs\,s^{-1}}$, since, averaged over a sufficient time scale, the kinetic power must exceed the radiative output of the jet. Similar arguments are commonly used in the analysis of Blazar emission (Ghisellini & Celotti 2001).

Detailed modeling of the spectral properties of the XTE J1118 jet has led Markoff et al. (2001) and Yuan & Cui (2005) to propose values of the kinetic power that translate to normalization values of $W_0 \approx 10^{38}\,{\rm ergs\,s^{-1}}$ and $2 \times 10^{37}\,{\rm ergs\,s^{-1}}$, respectively. It is important to note that the jet power in these models is essentially a free parameter, since parameters like the proton content and the opening angle of the jets are unkown. Nonetheless, these estimates show that reasonable parametrizations used in the literature for a variety of models are consistent with the estimate we presented in eq. (10). Malzac et al. (2004) argue for a lower limit of $W_0 \gtrsim 2 \times 10^{38}\,{\rm ergs\,s^{-1}}$ [higher but still consistent with our estimate in eq. (10) below] on the basis of their model for the timing behavior of the accretion flow. However, this model does not differentiate between a wind-like outflow and a jet (as long as the flow acts as an energy sink) and it is not clear how this limit can be turned into a constraint on the jet power alone.

Calorimetric observations (i.e., radio lobes, X-ray cavities, and shocks surrounding the cocoons of radio sources) are the most reliable way to estimate jet powers. Recently, evidence for the interaction of the Cygnus X-1 jet with its environment was discovered in the form of a ring of thermal emission that is probably the shock driven into the interstellar medium by a so far undetected radio lobe around Cygnus X-1 (Galloet al. 2005). The analysis of this shock indicates that the *average* jet power is $10^{36}\,{\rm ergs\,s^{-1}} < \langle W\rangle < 10^{37}\,{\rm ergs\,s^{-1}}$. As we will show in §3.2, this corresponds to a range of $5 \times 10^{36}\,{\rm ergs\,s^{-1}} < W_0 < 5 \times 10^{37}$, which is consistent with estimate we present in eq. (10).

While Circinus X-1 does appear to possess a radio lobe, it does not seem to show a similar shock as Cygnus X-1 does, and thus estimates of the source age are more difficult. Furthermore, it is still not entirely clear whether Circinus X-1 is a neutron star or black hole. (Heinz 2002) estimated the source power to be $\langle W\rangle \gtrsim 10^{35}\,{\rm ergs\,s^{-1}}$. This limit is consistent with that on Cygnus X-1 if the system is in fact a neutron star rather than a black hole, in which case we would expect the average source power to be smaller by about the mass ratio, roughly an order of magnitude.

Finally, (Kaiser et al. 2004) estimate the mean kinetic power of the jets in GRS 1915+105 from the tentative association with what appear to be two IRAS hot spots (Chaty et al. 2001, note that this association leads to distance estimates that are in marginally inconsistent with other measurements) to be $10^{36}\,{\rm ergs\,s^{-1}}\langle W\rangle < 10^{37}\,{\rm ergs\,s^{-1}}$. If a significant potion of the power in the GRS 1915+105 jet come from the compact/steady flow, this estimate is consistent with the estimate from above for Cygnus X-1 and again implies that

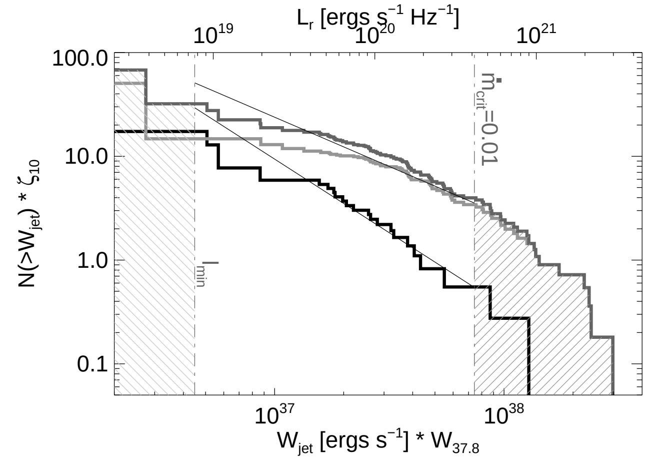

FIG. 1.— Estimate of the cumulative kinetic luminosity function for jets from low/hard state black hole XRBs for HMXBs (thin black line), LMXBs (thin grey line) and the total (thick grey line), and powerlaw approximation for high luminosities. Also shown (top axis) are the corresponding radio luminosities at 5 GHz, for which this plot shows the cumulative radio luminosity function.

$5 \times 10^{36}\,{\rm ergs\,s^{-1}} < W_0 < 5 \times 10^{37}\,{\rm ergs\,s^{-1}}$, and it is also very much in line with what we will estimate below based on AGN jets.

3.2. *The absolute kinetic power output of Galactic black holes in the low/hard state*

With the estimate of W_0 in hand, we can evaluate a number of important quantities. The first is simply the kinetic luminosity function for XRBs. The approximate analytic expression is given by eqn. (7) with the value of W_0 from eq. (10). Using the actual data of the XRB luminosity function by Grimm et al. (2002), we can also plot the kinetic luminosity function, as shown in Fig. 1.

The second is the total kinetic power released into the Galaxy by steady, flat spectrum jets from XRBs. It is simply the integral over the luminosity function:

$$W_{\rm tot} = \int dW_{\rm jet}\frac{dN}{dW_{\rm jet}}$$

$$W_{\rm HMXB} \approx 2 \times 10^{38}\,{\rm ergs\,s^{-1}}\,\mathcal{W}_{37.8}\zeta_{0.1}M_{10}^{0.55} \quad (11)$$

$$W_{\rm LMXB} \approx 3.5 \times 10^{38}\,{\rm ergs\,s^{-1}}\,\mathcal{W}_{37.8}\zeta_{0.1}M_{10}^{0.55} \quad (12)$$

Note that the power output from HMXBs is dominated by low luminosity sources - the total power estimate depends on the assumed lower cutoff and is thus a lower limit. For LMXBs, the total power is essentially a logarithmic function of the lower limit on W to lowest order, i.e., each decade in $W_{\rm kin}$ contributes the same amount of total power. At low luminosities, however, both the HMXB and the LMXB luminosity functions turn over, the radio-X-ray relation presumably breaks down, and the total number of XRBs is limited, so, as expected, the kinetic luminosity function does not diverge.

It is worth pointing out that the value for $W_{\rm tot}$ is somewhat larger than the estimated total energy output from low/hard state XRB jets presented in Heinz & Sunyaev (2002), which was derived from very different arguments (we should note that the estimate presented in this paper should be significantly more reliable). This also implies that the statements

made in that paper about the total contribution from XRB jets to the Galactic cosmic ray spectrum still hold (i.e., that the total contribution is small, however, spectrally unusual signatures like narrow lines or Maxwellian features *will* stand out measurably).

Given the estimated star formation rate of $3\,M_{\odot}\,\mathrm{yr}^{-1}$ of the Galaxy, and the fact that the HMXB luminosity function is a good estimator of the star formation rate (Grimm et al. 2003), we can estimate the total kinetic power output in other galaxies with known star formation rates by multiplying the HMXB kinetic luminosity estimate from (11) by the ratio of star formation rates relative to the Milky Way. The LMXB luminosity function does not scale like the star formation rate. Instead, it should scale like the total mass in stars (dominated by low mass stars), of which the LMXBs are a given fraction, which is slowly increasing with time beyond a stellar age of about a billion years.

Using the stellar mass of the Milky Way, we can also calculate the time integrated total energy that was released by low/hard state jets: The total stellar mass in the Milky Way is about $10^{11}M_{\odot}\mathcal{M}_{11}$. For a current star formation rate of $\dot{\mathcal{M}} \approx 3M_{\odot}\,\mathrm{yr}^{-1}\dot{\mathcal{M}}_3$, we can multiply the current power estimate from HMXBs by the star formation age of the Milky Way to derive an estimate of the total energy released by HMXB jets throughout the history of the Galaxy:

$$E_{\mathrm{HMXB,tot}} \approx 2.2\times10^{56}\,\mathrm{ergs}\,\mathcal{M}_{11}/\dot{\mathcal{M}}_3\mathcal{W}_{37.8}\zeta_{0.1}M_{10}^{0.55} \tag{13}$$

while for LMXBs, we should multiply the current energy output by the age of the LMXB population, which is about $10^{10}\,t_{10}\,\mathrm{yrs}$ such that

$$E_{\mathrm{LMXB,tot}} = 2.3\times10^{56}\,\mathrm{ergs}\,t_{10}\mathcal{W}_{37.8}\zeta_{0.1}M_{10}^{0.55} \tag{14}$$

The third quantity worth estimating from this distribution is the mean jet power of individual XRBs. The main uncertainty here is the variability of individual sources. Since the XRLF is a snapshot of the X-ray output from a large sample of sources, we will have to make an assumption about how variability of individual sources factors into the XRLF. For lack of better knowledge and for reasons of simplicity, we will consider two possible, simplified scenarios:

- The XRLF reflects the temporal X-ray luminosity distribution of each individual source. I.e., each source spends a fraction of its life proportional to $dN/dl_{\mathrm{x}}(l_{\mathrm{x}})$ in the luminosity bin $[l_{\mathrm{x}}, l_{\mathrm{x}}+dl_{\mathrm{x}}]$. The luminosity range spanned by transients is certainly comparable if not larger than the range spanned by $l_{\min}$ and $\dot{m}_{\mathrm{crit}}$, supporting this picture. Since the XRLF is rather steep, in this scenario an individual source therefore spends most of its life at low luminosities - as has long been known in the X-ray community to be the case for transient sources.

  The average kinetic luminosity of an individual source is simply the total kinetic luminosity of all XRBs divided by the number of black hole XRBs in the luminosity interval $10^{-4} < l_{\mathrm{x}} < 10\dot{m}_{\mathrm{crit}}M_{10}$:

$$\langle W\rangle_{\mathrm{HMXB}} \approx 1.7\times10^{37}\,\mathrm{ergs\,s^{-1}}\,\mathcal{W}_{37.8}M_{10}^{0.55} \tag{15}$$

  and

$$\langle W\rangle_{\mathrm{LMXB}} \approx 2.8\times10^{37}\,\mathrm{ergs\,s^{-1}}\mathcal{W}_{37.8}M_{10}^{0.55} \tag{16}$$

  These are very large numbers indeed, about 1-2% of the Eddington luminosity for a 10 solar mass black hole, *if* our estimate of $\mathcal{W}_{37.8}$ is at least of the right order of magnitude. This indicates that the kinetic energy transported by XRB jets is comparable to or larger than the radiative output: the integral over the luminosity functions in eqs. (5) and (6) gives average X-ray luminosities of $\langle L_{\mathrm{x,HMXB}}\rangle \sim 7\times10^{35}\,\mathrm{ergs}$ and $\langle L_{\mathrm{x,HMXB}}\rangle \sim 1.2\times10^{37}\,\mathrm{ergs}$. It also implies that the kinetic energy released in low luminosity states is at least comparable to the energy advected into the black hole (see also Fender et al. 2003).

  We can now compare these numbers with the limits from Cygnus X-1 and GRS 1915+105 from the previous section: $\langle W\rangle_{\mathrm{CygX-1}} > 10^{36}\,\mathrm{ergs\,s^{-1}}$ and $10^{36}\,\mathrm{ergs\,s^{-1}}\langle W\rangle_{1915} < few\times10^{37}\,\mathrm{ergs\,s^{-1}}$, which imply $0.1 < \mathcal{W}_{37.8} < few$, very much consistent with the estimate derived from AGN jets.

  In this scenario, all sources in either the HMXB or LMXB class are assumed to be very similar, which, given the diversity of X-ray binaries, is clearly a simplification. The fact that the XRLF is not altered by the variability of individual source (Grimm et al. 2005) somewhat supports this simplified picture and the assumption that we can average over the luminosity function to remove the effects of variability.

- Alternatively, we could consider a scenario where each source varies around an interval in W_{kin} much narrower than the width spanned by $l_{\min}$ and $\dot{m}_{\mathrm{crit}}$. In this case, individual sources differ from each other in average kinetic power, and the distribution of $\langle W\rangle$ is identical to the distribution of instantaneous power W. Still, the *ensemble averaged* kinetic luminosity function $\Phi(\langle W_{\mathrm{jet}}\rangle)$ is identical to the snapshot kinetic luminosity function $\Phi(W_{\mathrm{kin}})$ and the number derived for the total kinetic power is identical to eq. (11).

Neither of these scenarios is likely to be entirely correct; however, the range in W_{kin} spanned by the kinetic luminosity function in eq. (7) is relatively narrow and it is rather likely that individual sources traverse a range in W_{jet} that is at least as large as this. Thus, using the average value from eq. (15) for individual sources to estimate the effects on the interstellar medium appears to us to be a reasonable choice.

Finally we stress again that these estimates are based on an extrapolation from AGN jet power estimates, which themselves are somewhat uncertain and are thus working estimates only. Obviously, a much better and more accurate way to estimate W_{kin} for XRBs is a direct determination. We anticipate that conclusive measurements of W_0 from XRB radio lobes (Heinz 2002) are going to become available in the near future.

3.3. *Hysteresis and the critical accretion rate*

As hinted at in §1, the exact location of $\dot{m}_{\mathrm{crit}}$ is not only uncertain, sources actually show a hysteresis in transitioning from the high/soft state to the low/hard state and back. The transition from high/soft to low/hard typically occurs at lower luminosities than the reverse transition. Before elaborating as to how much this will affects our estimates, it is worth examining quickly what the effects of different values for $\dot{m}_{\mathrm{crit}}$ on $\langle W\rangle$ and W_{tot} actually are.

We have evaluated eqs. (11) and (12) for a range of values of $\dot{m}_{\mathrm{crit}}$ and fitted the results with a quadratic in log-log space.

For the total jet power, we find that

$$\log W_{\rm HMXB} \approx 38.34 + 0.05\,[\log(\dot{m}_{\rm crit}) + 2] - 0.238\,[\log(m_{\rm crit}) + 2]^2 + \log \mathcal{W}_{37.8}\zeta_{0.1} M_{10}^{0.55} \quad (17)$$

$$\log W_{\rm LMXB} \approx 38.58 + 0.38\,[\log(\dot{m}_{\rm crit}) + 2] - 0.151\,[\log(m_{\rm crit}) + 2]^2 + \log \mathcal{W}_{37.8}\zeta_{0.1} M_{10}^{0.55} \quad (18)$$

Since the mean jet power is simply the total power divided by the number of binaries, it has the same dependence on $\dot{m}_{\rm crit}$, but zero order different normalizations, as given by eqs. (15) and (16).

This demonstrates that our estimates are not very strongly dependent on $\dot{m}_{\rm crit}$ for values of $\dot{m}_{\rm crit} \gtrsim 0.01$. For LMXBs, the power changes by a factor of 1.7 when increasing $\dot{m}_{\rm crit}$ from 0.01 to 0.1. Given that the expected range in which this hysteresis occurs is about $0.01 < \dot{m}_{\rm crit} < 0.1$ (Fender et al. 2004b), we can estimate the effect by assuming that sources spend an equal amount of time on both the high/soft and the low/hard branches. Thus, a crude estimate would imply that about 50% of the sources above $\dot{m}_{\rm crit} > 0.01$ are still in the low/hard state and produce jets. This would increase our estimates of the jet power for LMXBs by 36%, well within the uncertainties of our estimates. HMXBs are essentially unaffected by this change because there are very few sources above $\dot{m} = 0.01$.

3.4. *Transient Jets*

As mentioned in the introduction, some XRBs display transient jet emission associated with rapid changes in their X-ray luminosity. These events can reach radio fluxes that are much larger than in the case of steady, compact jets produced in the low/hard state. The classic example of this kind of source is GRS1915+105 (Mirabel & Rodríguez 1994; Fender et al. 1999), the complex behavior of which is too diverse to be reviewed in the scope of this paper (see Fender & Belloni 2004, for a review of GRS 1915+105). Other transient sources for which this behavior has been observed include GRO J1655-40 (Hjellming & Rupen 1995), V4641 Sgr (Orosz et al. 2001), XTE J1748-288 (Fender & Kuulkers 2001), and XTE J1550- (Corbel et al. 2002) (see table 1 in Fender 2005, for more details). The radio emission from these events is typically optically thin and can be spatially resolved.

In several cases, superluminal proper motion has been detected (Mirabel & Rodríguez 1994; Hjellming & Rupen 1995; Fender et al. 1999; Corbel et al. 2002; Fender et al. 2004a), which implies relativistic velocities with Lorentz factors $\Gamma \approx 2 - 5$. The relative abundance of measurable parameters in the optically thin, partially resolved case makes it possible to estimate the total energy contained in the emission region and estimating the kinetic power in these transient jets. We shall briefly discuss these estimates and their implication for the total jet power from XRBs.

It is currently not understood what the relationship between the transient jet events observed during state transitions, and the steady compact jets observed in the low/hard state is. It is important to stress that we cannot use the power estimates from the transient events to normalize the low/hard state kinetic luminosity function. Because we have limited the kinetic luminosity function derived above to the luminosity range typically spanned by the low/hard state, our kinetic luminosity function and the quantities derived from it don't account for the separate component contributed by these transient jets by construction.

There are several reasons why we cannot simply expand our treatment to include these sources: (a) By their nature, these events are transient, and unlike in the low/hard state, a source may or may not be emitting a transient jet at a given X-ray luminosity in a given state. The fraction of time a transient source is emitting a transient jet at a given X-ray luminosity is unknown. (b) The radio-X-ray relation that we used to derive the relation between the X-ray luminosity and the radio luminosity does not hold for transient jets. (c) The emission from transient jets is optically thin, and thus the relation between radio emission and kinetic power in eq. (3) does not hold (which is one of the reasons why the radio-X-ray relation breaks down).

In the absence of statistical information about the relative duration, brightness, and kinetic power of individual transient jet events (which would be necessary to calculate the integrated transient jet power), we can still make an educated, though very rough guess of the contribution of these jets to the total kinetic power: For one thing, (Fender 2005) show that sources undergoing a hard–soft transition are known to produce transient jets, while they speculate that sources making a soft-hard transition do not. Thus, over some luminosity range at the transition luminosity from hard to soft state, we should expect a transient jet to be emitted in between 50% to 100% of the sources.

Secondly, Fender (2005) show that a relation between X-ray power and kientic power exists in transient jet sources and can be (roughly) calibrated to give

$$W_{\rm jet} = 1.3 L_{\rm Edd} l_{\rm x}^{0.5\pm0.2} \quad (19)$$

This relation is surprisingly close to the relation we used above for the low/hard state jets: $W_{\rm jet} = 1.8 L_{\rm Edd} l_{\rm x}^{0.42} \mathcal{W}_{37.8} M_{10}^{0.55}$, as already pointed out by Fender (2005).

Thus, if we knew the duty cycle ξ of transient events (i.e., the fraction of source above $\dot{m}_{\rm crit}$ which are producing transient jets), we could graft these two functions together at $\dot{m}_{\rm crit}$ to make one continuous kinetic luminosity function and integrate to get the total power. Since we have neither a functional form of the distribution of $\dot{m}_{\rm crit}$ nor the duty cycle of transient events above $\dot{m}_{\rm crit}$, we can only state that the expression in eq. (19) is statistically identical to eq. (4) and that the contribution from transient jets to the kinetic power should therefore be well described by eqs. (17) and (18) multiplied by ξ, which describe the dependence of the kinetic power on the value of $\dot{m}_{\rm crit}$.

As already pointed out in §3.3, increasing $\dot{m}_{\rm crit}$ by an order of magnitude only increases the kinetic power estimates by a factor of ≈ 1.7. Since the transient jet source fall on essentially the same kinetic luminosity function with an unknown duty cycle $\xi < 1$, the ratio of the kinetic power carried in transient jets to that carried in compact, steady jets should be roughly $0.7\xi/\mathcal{W}_{37.8}$. This gives a total power estimate of order $4\xi \times 10^{38}\,{\rm ergs\,s^{-1}}$ for transient jets.

On the other hand, we know from the observed number of outbursts that the total kinetic power from transient jets in the Galaxy is of the order of $few \times 10^{38}\,{\rm ergs\,s^{-1}}$ (Heinz & Sunyaev 2002), compared to the total estimated power of $\approx 5 \times 10^{38}\,{\rm ergs\,s^{-1}}$. Thus, based on the estimates of W_0 we provided above and the kinetic power normalization of transient jets by Fender et al. (2004b), the integrated kinetic powers of transient jets and of compact steady jets are of the same order of magnitude and the duty cycle of transient jets should not be much smaller than $\approx 10\%$.

3.5. *Neutron Stars*

As mentioned in §1, neutron stars are even less radio loud than black hole XRBs at typical X-ray luminosities. At the current time it is not entirely clear whether the FP relation of eq. (1) is applicable to neutron star systems as well: it is possible that a radio-X-ray relation exists for neutron stars, but has a different slope (Migliari et al. 2003), it is also possible that no such relation exists at all. In either case, an extension of our method is not easily possible. For simplicity, however, we will assume that the same correlation shown in eq. (1) holds for neutron stars as well, but with a different normalization.

Given the difference in radio loudness of a factor of ~ 30 at a fixed X-ray luminosity and taking into account the mass difference between neutron stars and black holes of about $M_{\rm BH}/M_{\rm NS} \sim 10/1.4$, this changes the normalization of eq. (1):

$$L_{\rm r} = \frac{1}{30}\left(\frac{10}{1.4}\right)^{0.78} L_0 l_{\rm x}^{0.6} M^{0.78} \qquad (20)$$

Consequently, the normalization of eqs. (8-9) changes as well:

$$\frac{dN_{\rm NS}}{dW_{\rm jet}} = \left[30\left(\frac{1.4}{10}\right)^{\frac{0.78}{1.42-\alpha_{\rm r}/3}}\right]^{-\beta} \zeta^{-1}\frac{dN_{\rm BH}}{dW_{\rm jet}} \qquad (21)$$

The numerical evaluation for $\beta = 1.6$ in the case of HMXBs gives only a slight change of 1.1, while $\beta = 1.4$ in the case of LMXBs gives 1.4. Note, however, that both ζ and the mass are going to be different for neutron stars. Taking these into account, the absolute normalization the kinetic luminosity function is increased by factors of 2.4 and 3.0 for neutron star HMXB and LMXB respectively, compared to black hole HMXBs and LMXBs.

Fender (2005) suggest that high-field neutron star systems do not produce jets, as they show no radio emission. Since a large fraction of the neutron star HMXBs are, in fact, X-ray pulsars (Liu et al. 2000) with associated high fields, the normalization of the kinetic luminosity function for HMXB neutron stars is likely smaller by at least a factor of 2 compared to the above estimate. Furthermore, all HMXBs are believed to have rather strong fields ($B \gtrsim 10^{12}\,$G), which Fender (2005) conjectured as being unable to produce jets at all. We therefore conservatively assume that the HMXB values below are upper limits.

Taking into account the lower X-ray luminosity that corresponds to $\dot{m}_{\rm crit} = 0.01$ in neutron stars, the estimates for the mean kinetic power from neutron star jets is $\langle W\rangle_{\rm HMXB} < 2.6 \times 10^{37}\,{\rm ergs\,s^{-1}}\mathcal{W}_{37.8}$ and $\langle W\rangle_{\rm LMXB} \sim 2.5 \times 10^{37}\,{\rm ergs\,s^{-1}}\mathcal{W}_{37.8}$. We can then estimate the total kinetic power from neutron stars into the Galaxy to be $W_{\rm LMXB} < 3.4 \times 10^{38}\,{\rm ergs\,s^{-1}}\mathcal{W}_{37.8}$ for HMXBs and $W_{\rm LMXB} \sim 3.3\times10^{38}\,{\rm ergs\,s^{-1}}\mathcal{W}_{37.8}$ for LMXBs. This brings the total kinetic power output from XRBs (black holes and neutron stars) to $W_{\rm XRB} \sim 9\times10^{38}\,{\rm ergs\,s^{-1}}$. Finally, the total energy released by neutron star LMXB jets over the lifetime of the Galaxy is $E_{\rm LMXB} \approx 2.2 \times 10^{56}\,{\rm ergs}\mathcal{W}_{37.8}t_{10}$.

4. A COROLLARY: THE RADIO LUMINOSITY FUNCTION AND RADIO LOGN-LOGS OF XRBS

Given the X-ray luminosity function for Galactic XRBs in eqs. (5) and (6) and the FP relation from eq. (1), we can easily write down the predicted Galactic radio luminosity function for this population of binaries:

$$\frac{dN}{dl_{\rm r}} = \frac{dN}{dl_{\rm x}}\frac{dl_{\rm x}}{d_{\rm r}} \qquad (22)$$

where, following the nomenclature from above, $l_{\rm r} = L_{\rm r}/L_{\rm Edd}$ is the radio luminosity in units of the Eddington luminosity of a one solar mass object. The top axis in Fig. 1 shows the predicted cumulative radio luminosity function.

For Galaxies with stellar populations of a similar age to the Milky way, the LMXB distribution should just be proportional to the mass M, while the HMXB distribution should be proportional to the star formation rate $\dot{M}$:

$$\frac{dN_{\rm HMXB}}{dl_{\rm r}} = 10^{-8.7} l_{\rm r}^{-2} M_{10}^{0.78}\zeta_{0.1} \qquad (23)$$

$$\frac{dN_{\rm LMXB}}{dl_{\rm r}} = 10^{-5.2} l_{\rm r}^{-5/3} M_{10}^{0.52}\zeta_{0.1} \qquad (24)$$

for $10^{-9} < l_{\rm r} < 3.2 \times 10^{-7}\dot{m}_{\rm crit}^{0.6}$. Again, while the total emitted radio power in the HMXB distribution seems to diverge logarithmically if the lower limit $l_{\rm r,min}$ goes to zero, the luminosity function is, of course, limited by the number of sources, which is not infinite. Furthermore, the radio spectrum will eventually become optically thin at low luminosities and the luminosity function will become flatter than the expression in eq. (22) and converge. Note that in X-ray binaries this transition happens at very low luminosities: For typical low/hard state sources, the break from optically thick to thin occurs in the infra-red, and the break frequency $\nu_{\rm b}$ roughly follows $\nu_{\rm b} \propto L_{\rm r}^{8/17}$ (Heinz & Sunyaev 2003). For the break to move below radio frequencies, we would have to consider radio fluxes 8 orders of magnitude below what is typically observed.

Finally, we can estimate the flux distribution from the radio luminosity function (log N - log S). The flat spectrum XRB radio flux distribution for a galaxy at distance D is simply $d\log N/d\log S = 4\pi D^2 d\log N/d\log l_{\rm r}$, since all sources are essentially at the same distance. Unfortunately, it is clear from the range in luminosities implied by Fig. 1 that sources in Galaxies further than about a Mpc will not be observable any time soon unless the population is large enough to contain significantly beamed sources (note that the verdict on how relativistic XRB jets actually are is still out - see, for example, the discussion in Gallo et al. (2003); Heinz & Merloni (2004); Kaiser et al. (2004); Narayan & McClintock (2005)).

To derive the predicted radio flux distribution in the Milky Way, we have to convolve the luminosity function with the space distribution of Binaries inside the Milky Way. Following (Grimm et al. 2002) and taking r and z to be the radial and vertical distance to the Galactic center, the disk populations is describe by the function

$$n_{\rm disk}(r,z) = \frac{e^{\left(-\frac{r_{\rm m}}{r}-\frac{r}{r_{\rm d}}-\frac{|z|}{r_{\rm z}}\right)}8\pi\, r_{\rm m} r_{\rm d} r_{\rm z}}{K_2\left(2\sqrt{\frac{r_{\rm m}}{r_{\rm d}}}\right)} \qquad (25)$$

with $r_{\rm m} \approx 4\,{\rm kpc},\ r_{\rm d} \approx 3.5\,{\rm kpc},\ r_{\rm z} \approx 410\,{\rm pc}$ for LMXBs and $r_{\rm m} \approx 6.5\,{\rm kpc},\ r_{\rm d} \approx 3.5\,{\rm kpc},\ r_{\rm z} \approx 150\,{\rm pc}$ for HMXBs, and K_2 is BesselK. The LMXB distribution also requires a spherical halo component, which we will assume to follow

$$n_{\rm halo}(R) = \frac{b^{8.5}e^{-b\left(\frac{R}{R_{\rm e}}\right)}}{16\pi\, R_{\rm e}^3\Gamma(8.5)}\left(\frac{R}{R_{\rm e}}\right)^{7/8} \qquad (26)$$

with $b \approx 7.7$ and $R_{\rm e} \approx 2.8\,{\rm kpc}$. Finally, about 30% of the disk sources reside in the Galactic center population, at about 8 kpc distance, for which we use the distribution

$$n_{\rm bulge}(R) = \frac{(R/R_0)^{-1.8}e^{-(R/R_{\rm t})^2}}{2\pi\,\Gamma[0.4]\,R_0^{1.8}\,R_t^{1.2}} \qquad (27)$$

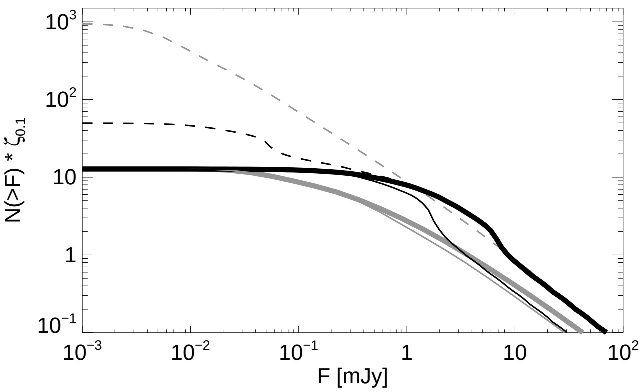

FIG. 2.— Estimate of the radio flux distribution of Milky Way X-ray binaries observed at solar radius. Grey: HMXBs, black: LMXBs. Thick solid lines: $l_{\min} = 10^{-4}, \dot{m}_{\rm crit} = 0.01$, thin dashed lines: $l_{\min} = 0, \dot{m}_{\rm crit} = 0.01$, thin solid lines $l_{\min} = 10^{-4}, \dot{m}_{\rm crit} = 0.001$.

with $R_0 = 1.0\,{\rm kpc}$ and $R_t = 1.9\,{\rm kpc}$.

The fraction of LMXBs in the halo is approximately 25% (including Globular Cluster sources). We will take the functional form of the luminosity function to be the same for the halo, bulge, and disk components. We then integrate over the luminosity function plotted in Fig. 1 and arrive at the flux distribution shown in Fig. 2 for different values of upper and lower cutoff $l_{\min}$ and $\dot{m}_{\rm crit}$. The thick lines indicate the fiducial luminosity interval of $10^{-4} < l_{\rm x} < 10^{-1}$. Note that these are time averaged curves. Temporal variability necessarily introduces large uncertainty at the high flux end, where few sources contribute at a given time.

Since we know at least one HMXB source which emits regularly at 10 mJy levels (Cygnus X-1) and a spectrum of other transient sources that regularly pass above the 10mJy line, the HMXB curve derived for the fiducial parameters can safely be regarded as a lower limit.

Clearly, the question of how far the X-ray luminosity function extends to lower luminosities and where the radio-X-ray relation breaks down has large implications for the number count of sources at lower fluxes. In other words, extending the sensitivity of XRB monitoring campaigns to lower fluxes will reveal rather quickly below which radio luminosity the predicted radio luminosity function breaks down.

Finally, it should be noted that this is essentially the probability distribution of finding a given binary at a given distance from earth, convolved with the predicted radio luminosity function. Since the actual number of XRBs is small, the error bars on this curve especially for large fluxes are probably large. However, a realistic assessment of the uncertainties in this distribution is beyond the scope of this paper.

5. CONCLUSIONS

Starting from the observed radio-X-ray-mass relation for accreting black holes and the observed X-ray luminosity function for XRBs, we derived the predicted kinetic luminosity function of compact jets from Galactic black holes in the low/hard state. The integration over the kinetic luminosity function of compact jets yields estimates of the average kinetic power output of $\langle W_{\rm jet}\rangle \sim 2 \times 10^{37}\,{\rm ergs\,s^{-1}}$ (dominated by LMXBs) and total integrated kinetic energy input over the history of the Galaxy of $E_{\rm tot} \sim 4.5 \times 10^{56}\,{\rm ergs}$. We argue that transient jets should carry a comparable amount of power. We also derived the predicted radio luminosity function and the radio flux distribution for XRB jets. These estimates can be used in future modeling of XRB jet parameters and provide a base line for estimating the impact of XRB jets in the interstellar medium.

After submission of this manuscript we became aware of a related paper (Fender et al. 2005) recently accepted for publication in MNRAS that reaches similar conclusions. We would like to thank Andrea Merloni, Mike Nowak, Rob Fender, and Rashid Sunyaev for helpful discussions and the anonymous referee for several important suggestions on how to improve this paper. Support for this work was provided by the National Aeronautics and Space Administration through Chandra Postdoctoral Fellowship Award Number PF3-40026 issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NAS8-39073.

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